APPLICATION OF NEW TECHNOLOGIES TO INTERISLAND POWER CABLES FOR HAWAII

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ABSTRACT

Any Hawaiian approach to an interisland electrical power network must confront two serious problems. First, the primary potential sources of natural power are on the Big Island, while the primary power consumers will (for the forseeable future) be on Oahu. Second, the first channel (Alenuihaha) that any cable must cross in bringing electrical power from Hawaii to Oahu has a depth of more than 2000 meters. This is almost 4-times deeper than any channel ever crossed by an undersea power cable. These problems may prove fatal if their solutions are constrained by the use of conventional cable designs or conventional materials; e.g., such low-strain materials as annealed copper and soft lead. Examples of new materials and approaches include:

- o Undersea, single-conductor, DC power cables have operated in Europe over distances of 130 kilometers, and with seawater return currents as great as 1000 amperes. The simplicity (and cable symmetry) inherent in this approach can be of enormous benefit to a Hawaiian interisland power cable.

- o Work-hardened copper wires can be cabled, with little or no conductivity penalty, so that they have 3- to 4-times the elastic strain limit of the conventional (soft annealed) form of this metal. This massive fraction of the power cable can therefore support (at least) its own weight during any deployment to the deepsea floor.

- o DuPont's KEVLAR-49 has shown excellent performance in deep ocean cables because of its high modulus, high strength and very high ratio of strength to in-water weight. (This last parameter is about 25-times greater in KEVLAR-49 than it is in cabling steels.)

- o Flexible and tough cabling steels are now available with ultimate tensile strengths greater than 20,000 kg/sq-cm.

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INTRODUCTION

Hawaii must face an extremely serious geographic mismatch between those domestic sites which have the natural resources to support production of electrical power and those sites on which are located the major anticipated consumers of such power. Power production should occur primarily on the Big Island of Hawaii. But the predominant power users (in this century) will be on other islands, separated by at least one ocean channel from Hawaii (Figure 1). And the first channel---Alenuihaha---that must be crossed by any cable run from Hawaii is by far the deepest yet faced by any undersea power cable (Table 1).

The deepest cable crossing achieved to date is the 125-km Skagerrak Sea between Norway and Denmark (Ref. 1---4). This channel is almost 3-times wider than Alenuihaha (Figure 2), but is barely one-fourth as deep.

Two years ago, I visited Standard Telephone og Kabel-fabrik in Oslo. This is the Norwegian company that designed, built and deployed the Skagerrak power cables. The STK briefing included the following highlights.

(1) Two cables were laid, in 1976 and 1977. Each was capable of transferring 250 megawatts across the Skagerrak Sea.

(2) Electrical operation of each cable was symmetric. That is, electrons could flow through the cable in either direction according to the commercial need.

(3) The supply voltage to each cable was 250,000 VDC, and cable insulation was subjected to a voltage stress of about 23,000 VDC/mm. (This is at least 10-times greater than the highest stress normally allowed in deepsea engineering cables.)

(4) During its first year, the 1976 cable was operated with a seawater circuit return (until the second cable was laid). The electrical current needed to support this circuit across the Skagerrak Sea was about 1000 amperes.

(5) Cable resistance was 2.87 ohms over 130 km---slightly less than the 4-ohm resistance of a seawater return. After the installation of the second cable in 1977, it became more efficient to use a cable circuit return. The STK engineers insisted that this was the only reason for the conversion. They also noted that seawater current densities were so low they could not be measured even a few kilometers offshore.

(6) While the Skagerrak cable's strength and strength-to-weight ratios were more than adequate for the planned deployment, that cable would have reliably failed due to the tensile stresses caused by in-water weight if it had been laid across the Alenuihaha Channel.

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THE SKAGERRAK CABLE

Figure (3) is a photograph of the Skagerrak undersea power cable. Table (2) gives details of cable construction. Data in the table are derived from an incomplete description of cable geometry and performance (Ref. 2) and, for this reason, are presented only as a "Skagerrak-like" design. The table also states several assumptions which became necessary in order to adequately interpret the reference.

The Skagerrak cable is described as having an air weight of 48 kg/m, and to suffer a tensile strain of less than 0.1% at a tensile load of 25 metric tons. The implication (Ref. 2) is that cable strain must be kept less than 0.1% during laying to avoid permanent straining of the copper conductor and lead sheath. The cable was also exposed to post-deployment cyclic strains of about ±0.15% (Ref. 3), caused by periodic changes in both the magnitude and the direction of the electrical current.*

Table (3) uses the design data and assumptions of Table (2) to reconstruct weight and strength for the Skagerrak power cable. Notice that cable tensile load is defined at a relative strain of 0.1%. Cable "free length" is that length which---hung vertically over the side of a ship in seawater with a specific gravity of 1.04---will cause a cable strain of 0.1%. For cable specific gravity σ, air weight W and allowable tensile load L, this length is equal to:

$$F = \frac{\sigma \cdot L}{(\sigma - 1.04)W} \quad \text{meters} \qquad (1)$$

TabLe (3) lists F-values for the components of the Skagerrak cable. It also gives the composite value (1660 m) for that parameter. Note that F is appreciably less than the maximum depth of the Alenuihaha Channel---the Skagerrak cable would fail during any deployment there. The peak (static) load experienced by that cable in our application would be approximately 74 metric tons. The corresponding load was 23 tons during the crossing of the Skagerrak Sea (Ref. 2).

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* In the Norway/Denmark power system, coal-derived electrical power is sent to Norway through the Skagerrak cable during periods of low stream flow in that country. Normally, however, the cable transfers Norwegian hydroelectric power in order to reduce Danish consumption of fossil fuels. Such load cycling should be a null problem in Hawaii, where user needs and system economics will (for many years) require a steady-state (baseline) flow of electrical power away from the Big Island.

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DESIGN SOLUTIONS

The Skagerrak power cable was admirably designed for its assignment, and has been successfully performing that task for nearly 8 years. But---in the context of an Alenuihaha Channel crossing---the Skagerrak design has two mortal deficiencies.

(1) Usable cable strength is seriously reduced by the constraint that tensile strain during deployment be limited to Ø.1%. This allows less than 2Ø% of the strength of the loadbearing armor to be used. Copper and lead are available in alloys and tempers which provide elastic strain limits considerably greater than Ø.1%. This low strain limit was quite adequate for the 53Ø-meter maximum depth of the Skagerrak Sea, but it puts an impossible burden on an Alenuihaha power cable.

(2) Many parts of the Skagerrak cable---especially its jackets, sheaths and insulation---made no meaningful contribution to strength. The fact that they also added little to in-water weight is relatively unimportant. The important point is that these bulky components could have readily been given additional functions within the cable.

Higher-strength steel could have been used for the armor. However, steel's tensile modulus is relatively independent of strength. Therefore, an "improvement" of this type adds little or no tensile capacity in a cable which (see above) is already subject to a much more serious limit on axial strain.

Table (4) suggest three modifications that can give the Skagerrak cable the free length needed in the Alenuihaha channel. The first two of these design changes changes are intended solely to increase the cable's elastic strain limit by modifying the copper conductor and the lead sheath. These two cable components are the ones most succeptible to tensile yield.

CONDUCTOR The Skagerrak Sea cable employed a soft (annealed) copper conductor, assumed to have a conductivity of 1Ø1% relative to the IACS standard. Typical yield strength for this copper---defined by a Ø.2% strain offset---is 21ØØ kg/squ-cm (Ref. 5). The yield strength can be increased by work-hardening the metal to a "hard" temper (29ØØ kg/squ-cm) or "spring" condition (35ØØ kg/squ-cm). At either of these tempers, the copper can readily withstand a cable-laying strain of Ø.2% without permanent tensile stretch.

The worst penalty that might accompany such work hardening would be a 3% (absolute) conductivity loss for the copper (Ref. 6).

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LEAD SHEATH

We must also be able to apply at least Ø.2% strain to this extremely ductile cable member. But the lead shell lies farther from the cable neutral axis than does the conductor, and it has no helix construction to give a measure of strain relief during tensile- or bending stresses. Any strain-tolerant solution must be found within the alloys of lead. (Copper and aluminum are ruled out here because of the high temperatures needed to extrude or weld them to form hermetic enclosures around the electrical core. Otherwise, either of these metals would be a viable material candidate.)

Table (5) summarizes physical properties of three candidate lead alloys, and compares them to the properties of commercially pure lead (Ref 7---9). Alloy F-3 was used in the Skagerrak cable. The antimony alloy is also commonly used for cable sheaths, and has a Ø.15% strength/modulus ratio. This is less than the desired value of Ø.2Ø%. But it is 5Ø% greater than the strength/modulus ratio of the F-3 alloy---which was allowed to experience ±Ø.15% strain cycling on the Skagerrak seafloor. This probably means that the lead/antimony alloy can be safely subjected to a Ø.2% tensile strain during the short time needed to lower a cable to the bottom of the Alenuihaha Channel.

Table (5) also lists the properties of a "Babbitt" alloy to show that available lead alloys can meet the Ø.2% strain criterion. Note that the melting point of this alloy is much lower than that of the F-3 lead. During extrusion of the lead sheath, this should help to reduce the danger of damage to the underlying polyethylene sheath.

INSULATION

In the Skagerrak power cable, an annulus of paper tape was wrapped around the copper conductor, and its cellular structure was completely impregnated with a high-viscosity mineral oil. The composite structure became the conductor insulation. In the design modification proposed here, the filaments in the paper tape are replaced with filaments of KEVLAR-49, a ultra-high-strength organic material produced by DuPont (Ref. 1Ø). KEVLAR's utility in undersea cables is well documented (Ref. 11 & 12), and need not be repeated here.

While KEVLAR has excellent dielectric properties (roughly comparable to those of fused quartz), it is asked only to assume the same role required of the paper tape. That is, the KEVLAR will serve as a neutral filamentary structure---supporting and containing the oil, which is the true insulator.

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CHARACTERISTICS OF ALENUIHAHA/SKAGERRAK CABLE

Table (6) summarizes the effects of these modifications on the weight, strength and free length(s) of the "Skagerrak-like" undersea power cable. Note that component cross sections are the same as before---no changes have been made in the cable geometry. In fact, the only design changes attempted have been the temper of the copper conductor, the alloy used in the lead sheath, and the replacement of paper with KEVLAR-49 in the insulation.

What if we use some of these design changes, but not all of them? What if all material/temper designs are acceptable, but the cable is operated at a limiting strain somewhat less than 0.2%? Several of these options are listed below. The first entry in the table is the Skagerrak cable design, strained only to the limits allowed in that system. The final entry matches Table (6), and represents full incorporation of all modifications to both cable design and deployment strain constraints. Other entries lie somewhere between these two extremes.

Design Modification	Strain "X"	Weight In Air (kg/m)	Load (kg) At Strain "X"	Free Length (m)
1. No Change.	0.10%	48.0	59,000	1660
	0.15%	48.0	<88,000	<1844
	0.20%	48.0	<118,000	<2460
2. Insulation Only.	0.10%	46.4	73,900	2180
	0.15%	46.4	111,000	3280
3. All Three Changes.	0.10%	46.2	73,300	2180
	0.15%	46.2	110,000	3270
	0.20%	46.2	147,000	4360

Notice that the design in which only the insulation has been modified just meets the Alenuihaha depth constraint, even at 0.1% tensile strain. The same is true when all three modifications are incorporated. Scenario #1 is a close approximation of the situation in which only the conductor and lead sheath have been modified. For that case, a full 0.2% tensile strain capability will be needed if the cable is to survive deployment across the Alenuihaha channel.

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CONCLUSIONS

1. Use of a single-conductor DC cable with seawater return is recommended for the Alenuihaha Channel crossing. If the interisland power system grows to the point where a second power cable is needed, we will have the option to drop the seawater return and operate the two cables as a pair.

2. Materials which are non-yielding to a strain of 0.2% are available for both the copper conductor and the lead sheath in the Skagerrak power cable. These changes---considered alone---can make it possible for such a cable to be safely deployed across the Alenuihaha Channel between Hawaii and Maui. But the safety margin will be small.

3. Serious consideration should be given to replacing the low-strength paper in the Skagerrak insulation with a benign material which combines good electrical properties with high strength and low in-water weight. DuPont's KEVLAR-49, with a specific gravity of 1.44, a filament tensile modulus of 1,290,000 kg/squ-cm and a filament ultimate tensile strength of at least 28,000 kg/squ-cm, is suggested as a candidate.

4. In laying the Alenuihaha cable, a major effort must be made to make the cable's radius of curvature as large as possible whenever it is under high tensile stress. The Skagerrak Sea deployment allowed an overboarding sheave with a diameter of 10 meters. This caused a curvature-induced cable strain of ±0.6% in addition to the (much smaller) tensile strain imposed by the cable's in-water weight. It is recommended that a "stinger" boom, of the type used to lay offshore pipelines, be employed in the Alenuihaha Channel.

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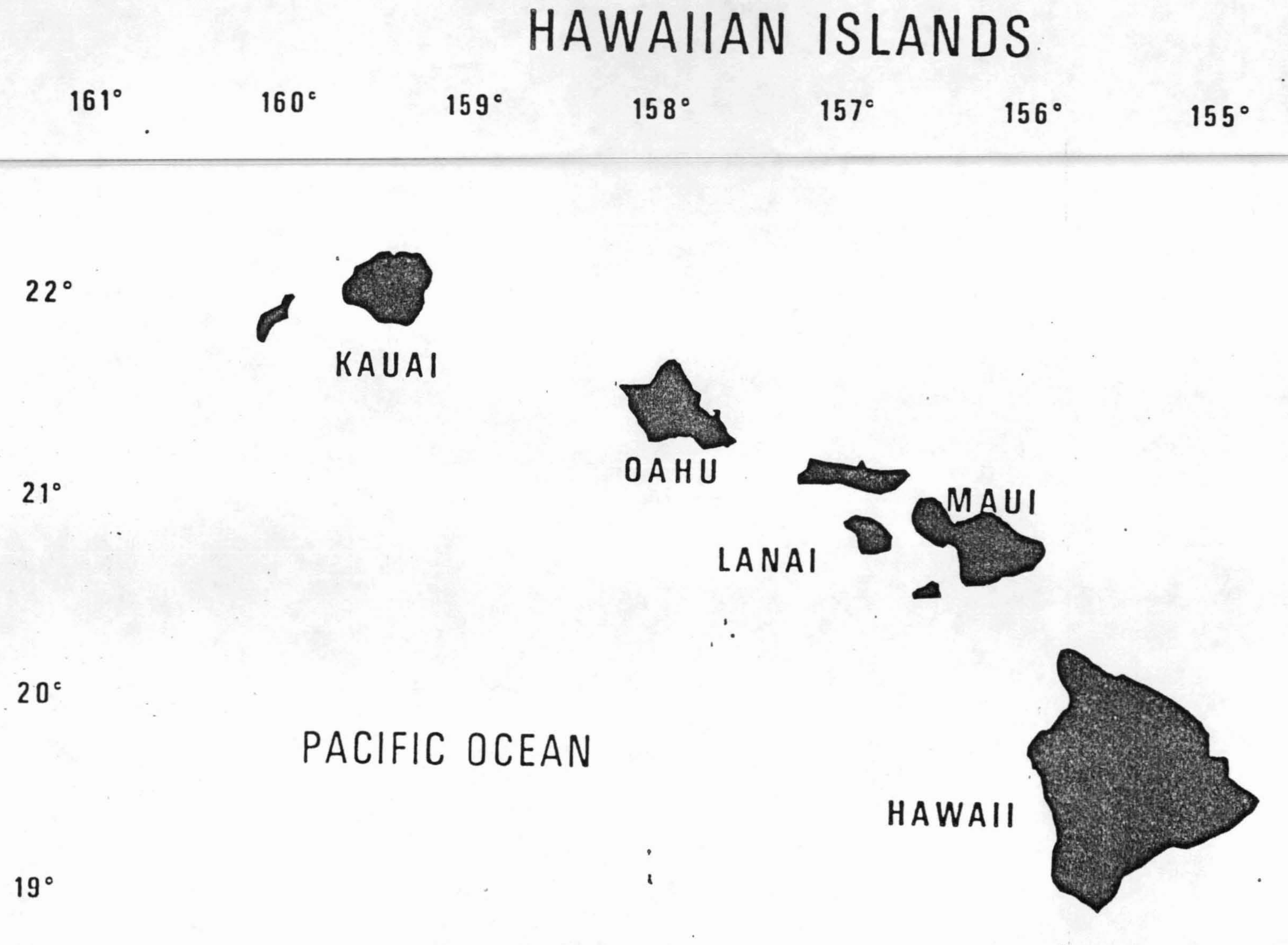

Figure (1)

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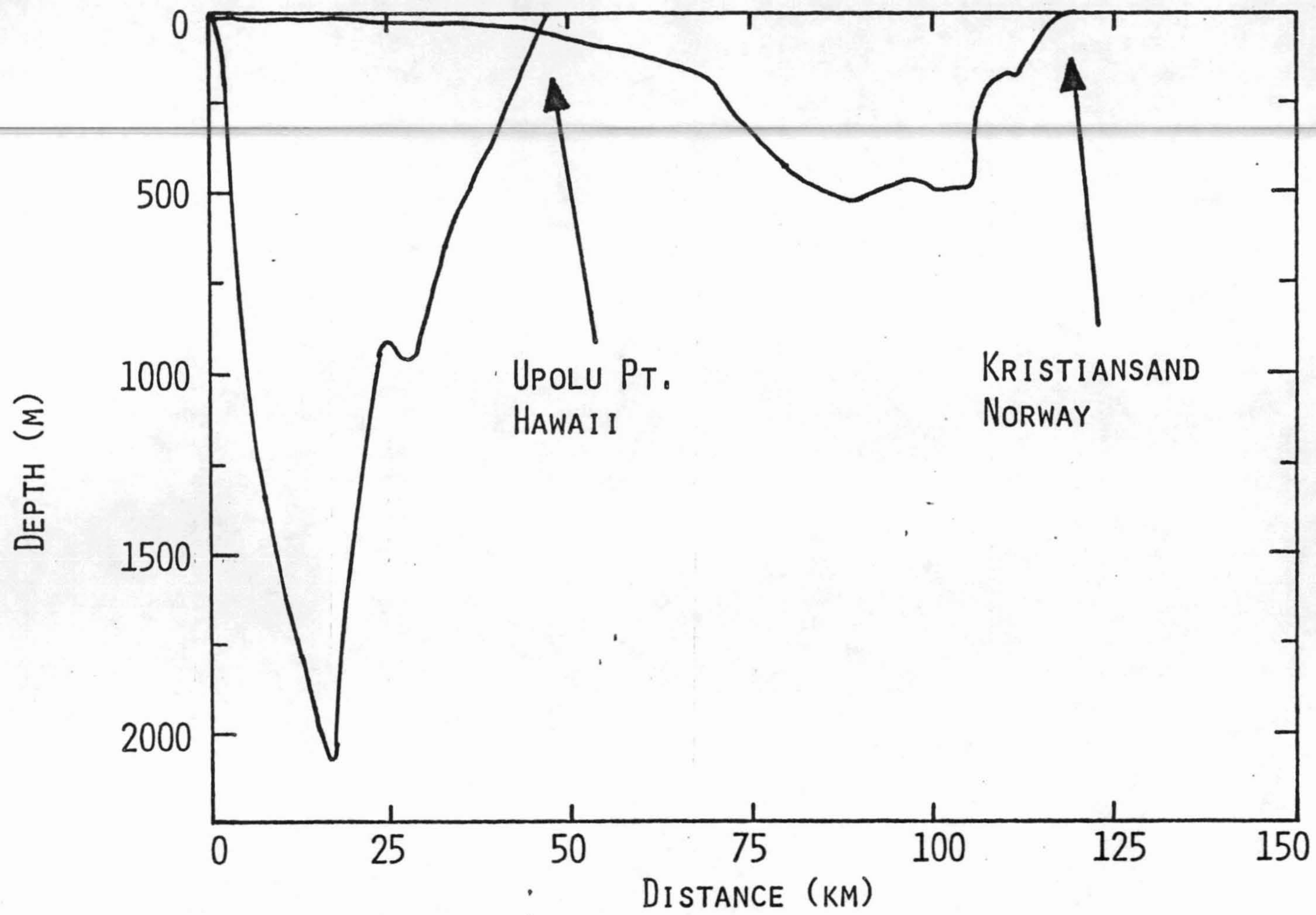

RELATIVE DEPTH CONTOURS FOR SKAGERRAK AND ALENUIHAHA CHANNELS

Figure (2)

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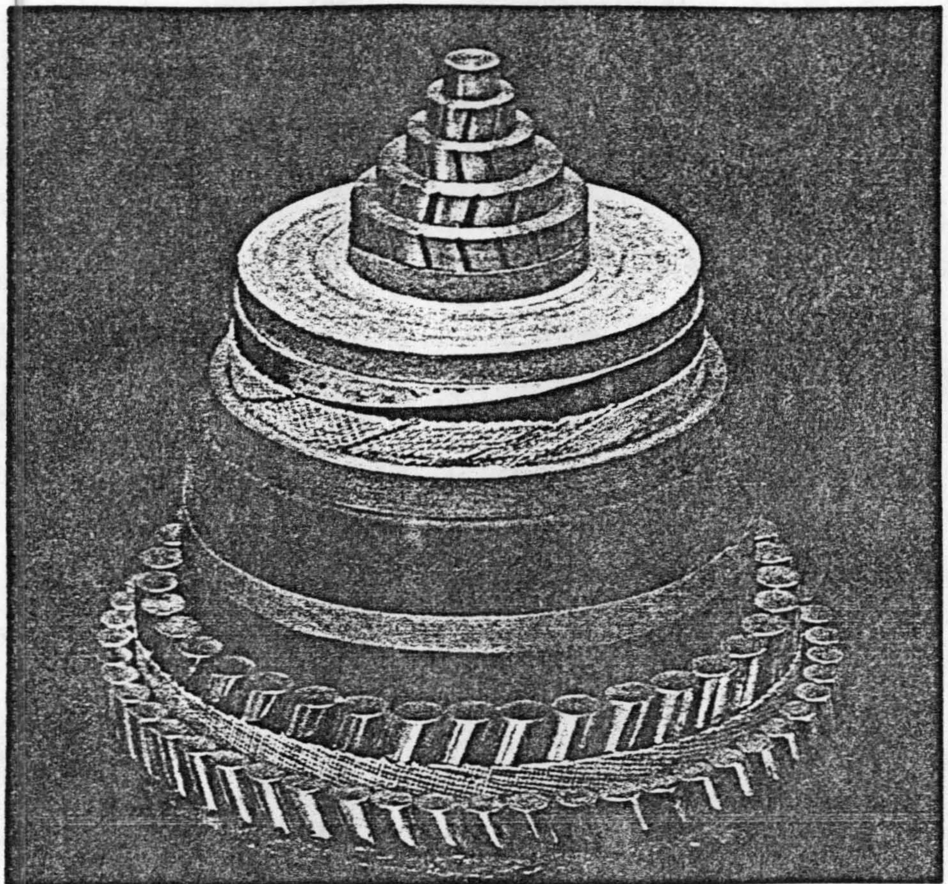

THE SKAGERRAK UNDERSEA POWER CABLE.

Figure (3)

ADJACENT ISLANDS	CHANNEL NAME	CHANNEL WIDTH (KM)	MAXIMUM DEPTH (M)
HAWAII---MAUI	ALENUIHAHA	47.6	2076
MAUI---KAHOOLAWE	ALALAKEIKI	10.8	251
MAUI---LANAI	AUAU	15.3	77
MAUI---MOLOKAI	PAILOLO	14.2	258
LANAI---KAHOOLAWE	KEALAIKAHIKI	28.6	331
LANAI---MOLOKAI	KALOHI	14.8	165
MOLOKAI---OAHU	KAIWI	41.5	671
OAHU---KAUAI	KAUAI	116.0	3319
KAUAI---NIIHAU	KAULAKAHI	27.7	1088

SOURCE: STATE OF HAWAII DATA BOOK, 1981.

CHANNELS OF THE HAWAIIAN ISLANDS

Table (1)

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CONDUCTOR	(SOFT COPPER) 4-LAYER L-R-L-R CONTRA-HELIX (15^{0}) OF SWAGE-SHAPED MEMBERS AROUND SOLID ROD TO 32-MM O.D.
INSULATION	PAPER TAPES, IMPREGNATED WITH HIGH-VISCOSITY MINERAL OIL TO 64-MM O.D.
LEAD SHEATH	ALLOY F-3 TO 71-MM O.D.
JACKET	POLYETHYLENE (HDPE?) EXTRUDED TO 77.2-MM O.D.
1ST ARMOR	(7-MM MILD STEEL) ASSUMED TO BE 34 WIRES SERVED WITH 20^{0} (LEFT) HELIX.
2ND ARMOR	(5.6-MM MILD STEEL) ASSUMED TO BE 49 WIRES SERVED WITH 20^{0} (RIGHT) HELIX.
JACKET	(NOT DESCRIBED) ASSUMED TO BE JUTE/TAR TO FINAL 124-MM DIAMETER.

ESTIMATED STRUCTURE OF SKAGERRAK UNDERSEA POWER CABLE.

Table (2)

REPRODUCED AT GOVERNMENT EXPENSE

COMPONENT	SPECIFIC GRAVITY	CROSS SECTION (CM^2)	WEIGHT IN AIR (KG/M)	LOAD (KG) AT 0.1% STRAIN	FREE LENGTH* (M)
CONDUCTOR	8.89	8.0	7.1	9,300	1480
INSULATION	2.00	24.1	4.8	150	63
LEAD SHEATH	11.35	7.4	8.4	1,150	150
HDPE SHEATH	0.95	7.2	0.7	30	----
1ST ARMOR	7.85	14.0	11.0	25,100	2640
2ND ARMOR	7.85	12.9	10.1	23,100	2640
JACKET	1.25	47.3	5.9	170	170
TOTALS	3.97	120.9	48.0	59,000	1660

* HANGING LENGTH WHICH CAUSES 0.1% STRAIN IN MEDIUM WITH $\sigma = 1.04$

PHYSICAL CHARACTERISTICS OF "SKAGERRAK-LIKE" UNDERSEA POWER CABLE.

Table (3)

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THE FIRST TWO CHANGES ALLOW ALL CABLE ELEMENTS TO SAFELY EXPERIENCE A 0.2% TENSILE STRAIN.

CONDUCTOR:	WORK HARDEN THE COPPER TO AT LEAST A FULL-HARD TEMPER. DO NOT ANNEAL AFTER SWAGING AND SHAPING. (ASSUME SECANT MODULUS IS REDUCED BY 5%.
METAL SHEATH:	REPLACE THE F-3 LEAD WITH AN ALLOY OF LEAD WITH TIN AND/OR ANTIMONY. (ASSUME MODULUS DOES NOT CHANGE.)

A THIRD CHANGE ADDS TENSILE MODULUS AND TENSILE STRENGTH TO THE CONDUCTOR INSULATION.

INSULATION:	REPLACE PAPER TAPES WITH KEVLAR-49 ROVINGS. (50% OF THIS ANNULUS IS FILLED WITH KEVLAR FILAMENTS & THE REMAINDER WITH INSULATING OIL. THE FILAMENTS HAVE A TENSILE MODULUS OF 1,290,000 KG/CM^2, AND ARE SERVED WITH A 15^O HELIX.)

MODIFICATIONS TO "SKAGERRAK-LIKE" UNDERSEA POWER CABLE.

Table (4)

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Parameter	"Corroding"	"Arsenical" Alloy F-3	1% Antimony	"Babbitt" Alloy 13
1. Composition (%)	99.94 Pb	Rest Pb 0.10 Sn 0.15 As 0.10 Bi	99.00 Pb 1.00 Sb	85.00 Pb 10.00 Sb 5.00 Sn
2. Specific Gravity	11.34	11.33	11.2	10.5
3. M. Point (^{o}C)	327	327	320	256
4. Fr. Point (^{o}C)	---	302	312	240
5. Tensile Strength (kg/cm^2)	142	211	211	703
6. Elastic Modulus ($kg/cm^2/1000$)	141	214	141	295
7. Strength/Modulus	0.10%	0.10%	0.15%	0.24%
8. Hardness (HB)	3---5	6---7	7	20

COMPARISON OF FOUR LEAD ALLOYS.

Table (5)

REPRODUCED AT GOVERNMENT EXPENSE

COMPONENT	SPECIFIC GRAVITY	CROSS SECTION (CM^2)	WEIGHT IN AIR (KG/M)	LOAD (KG) AT 0.2% STRAIN	FREE LENGTH (M)
CONDUCTOR*	8.89	8.0	7.1	17,600	2,800
INSULATION*	1.35	24.1	3.2	30,100	42,000
ALLOY SHEATH*	11.0	7.4	8.2	2,300	280
HDPE SHEATH	0.95	7.2	0.7	50	----
1ST ARMOR	7.85	14.0	11.0	50,200	5,300
2ND ARMOR	7.85	12.9	10.1	46,300	5,300
JACKET	1.25	47.3	5.9	170	170
TOTALS	3.82	120.9	46.2	147,000	4,360

* THE COMPOSITIONS OR TEMPERS OF THESE COMPONENTS HAVE BEEN MODIFIED.

CHARACTERISTICS OF MODIFIED SKAGERRAK U/S POWER CABLE.

Table (6)

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